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Research article

Risk of invasive species spread by recreational boaters remains high despite widespread adoption of conservation behaviors

Ellen Cole[1], Reuben P. Keller*, Kelly Garbach[2]

Institute of Environmental Sustainability, Loyola University Chicago, 1032 W. Sheridan Rd., Chicago, IL 60660, USA

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ABSTRACT

The spread of non-native aquatic species among waterbodies has become a major social, environmental, and economic concern. An important mechanism of this spread is the inadvertent transport of organisms on recreational boats as they are moved among waterbodies. Organisms can survive on the exterior of the boat, the interior, attached to fishing tackle, and can be intentionally moved by boaters. In response, local, state, and federal U.S. agencies have invested in outreach campaigns to educate boaters about the impacts of invasive aquatic species and the ways that boaters can reduce the risk of spread. We surveyed boaters in the U.S. state of Illinois to determine their travel patterns and how frequently they clean different parts of their boats. A majority of boaters reported that they always take recommended actions to clean their boat exterior (72% of respondents), boat interior (78%), and fishing tackle (55%), and only 4% reported that they intentionally move organisms. We used network methods to analyze the movement of recreational boaters and found strong connections among 28 highly visited waterbodies. When we removed the 38% of respondents who *Always* take recommended actions to reduce risk of species spread by all four mechanisms this network was minimally altered and still contained all 28 waterbodies. This indicates that despite high adoption of conservation behaviors there is a continuing risk of non-native species transport among all waterbodies. This work shows that further action is necessary if the impacts of invasive aquatic species are to be reduced in the future.

1. Introduction

The introduction and spread of aquatic non-native species by recreational boaters presents a clear example of feedbacks within a coupled human-natural system. Boaters select waterbodies to visit based on the ecosystem services offered by each river or lake, including the quality of fishing and other recreational activities. As boaters travel they can inadvertently transport harmful invasive species from previously visited lakes (De Ventura et al., 2016; Johnson et al., 2001; Rothlisberger et al., 2010; Schneider et al., 1998). If these species survive transport, are released into the new waterbody, and become established, they may reduce the ecosystem services available and provide a feedback that affects human use of the waterbody. Boaters may also intentionally move species – such as sport fishes – that they believe will make a waterbody more desirable (Mills et al., 1993). Once non-native species become established it is often not feasible to eradicate or control their populations, and the invaded waterbody becomes a source for further spread of the species.

Recreational boating is a popular activity across the Laurentian Great Lakes region of North America and has been responsible for the movement of non-native species among lakes and rivers (Campbell et al., 2016; Rothlisberger et al., 2010). A range of vectors has introduced non-native aquatic species to the Great Lakes, and in many cases these species have been spread among inland lakes and rivers by recreational boats. Examples of this process are the zebra (*Dreissena polymorpha*) and quagga (*D. rostriformis buggensis*) mussels, both of which were introduced to the Great Lakes by inter-continental ships (Mills et al., 1993). These species have spread to isolated waterbodies throughout the region (Benson, 2014), largely as a result of transport on recreational boats. Zebra and quagga mussels filter out much of the algal production in waterbodies and cause trophic effects that extend up the food-web to reduced production of valuable sport fishes (Higgins, 2014; Strayer et al., 2004). Additionally, Dreissenid mussels grow in dense populations that can foul infrastructure such as out-take pipes and docks, and their sharp shells can make swimming dangerous (Pimentel et al., 2005). Dreissenid mussels were moved to the Colorado River Basin on trailered boats and are now found as far west as California (Benson, 2014; Bossenbroek et al., 2007). Many other non-native

* Corresponding author.
E-mail address: rkeller1@luc.edu (R.P. Keller).
[1] Present address: Plant Biology Department, Michigan State University, 612 Wilson Rd., East Lansing, MI 48824, USA.
[2] Present address: Point Blue Conservation Science, 3820 Cypress Drive #11, Petaluma, CA 94954, USA.

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species have been transported around the Great Lakes region by recreational boaters, including plants (e.g., water milfoil (*Myriophyllum spicatum*)), other mollusks (e.g., Chinese mystery snail (*Cipangopaludina chinensis*)) and crayfishes (e.g., rusty crayfish (*Faxonius rusticus*)) (Kelly et al., 2013; Rothlisberger et al., 2010).

The sheer number of recreational boats moving across the landscape, combined with the large number of waterbodies that can be a source or recipient of invasive species, make this a particularly difficult environmental issue to manage. In some regions boats are directly inspected as they are removed from, transported between, or about to be launched on, waterbodies. For example, a program in the U.S. state of Idaho includes inspection stations that operate near state borders and some major waterbodies (Idaho Department of Agriculture, 2018). However, inspection stations are costly to manage and in most regions public education and outreach has been the preferred management tool. State and federal agencies, as well as non-profit organizations, use multiple types of media, events, and personal communication to inform boaters about aquatic invasive species (AIS) and how their behaviors can help prevent undesirable introductions and spread (Cole et al., 2016; Kemp et al., 2017). For example, the *Protect Your Waters* campaign has operated across much of the United States for over a decade (U.S. Fish and Wildlife Service, 2015). The campaign has used signs at boat ramps, stickers for cars and fishing gear, and booths at boat shows to transmit the message that boaters should make efforts to remove all plants and animals before transporting boats and other equipment, clean and dry their equipment, eliminate water from their equipment, and never intentionally transport and release any plants or animals (U.S. Fish and Wildlife Service, 2015). While this program and others like it have been widely employed, they have not been rigorously assessed to determine whether they actually change boater behaviors and lead to reduced rates of invasive species spread (Cole et al., 2016). Instead, most assessments of outreach programs have been based on the number of contacts with boaters, and/or have asked boaters – often immediately after they have received outreach – what their future behaviors will be.

Gravity and diffusion models have been used to explain and predict the landscape level movement of recreational boaters and the associated spread of AIS (e.g., Muirhead and MacIsaac, 2011). These models use basic boater information (e.g. number of registered boats, travel distance among waterbodies, frequency of visits to waterbodies), waterbody *attractiveness* (a metric of how likely boaters are to visit a given waterbody vs. other waterbodies), and habitat suitability for non-native species (Leung et al., 2006; Buchan and Padilla, 1999; Muirhead and MacIsaac, 2011; Schneider et al., 1998). While these models are useful because they can investigate the potential for AIS transport across large regions, they are limited because they make the critical assumption that all boaters perform behaviors that reduce invasion risk at the same rate. That is, they assume that any given boater traveling any given route will have the same risk of introducing non-native species. In reality, different boaters clean their boats and equipment at different rates meaning that risk of AIS spread is dependent upon individual boaters (Rothlisberger et al., 2010; Cole et al., 2016; Kemp et al., 2017).

In this paper we use individual-level self-reported survey data to determine how the behavior of recreational boaters may affect the chance of species spread across a landscape that contains many waterbodies. We focus on Illinois, a U.S. state that borders both the Great Lakes and the Mississippi River, and which is subsequently important for the spread of AIS throughout North America (Jacobs and Keller, 2017). Our survey results allow us to determine a subset of frequently visited Illinois waterbodies and to use social network analysis (Scott, 2000) to investigate the sequence in which boaters move among these waterbodies. We combine this with survey data on the frequency of boater engagement in behaviors that can reduce spread of non-native species. Analyzing these data in a network framework allows us to integrate actual travel patterns of recreational boaters and their individual level risk of AIS spread.

2. Methods

2.1. Survey of registered boaters

In July, 2014, we mailed 6000 surveys to Illinois residents who held boat registrations. Boater registration information was from 2013 and obtained from the Illinois Department of Natural Resources. We selected 12 counties throughout Illinois (see Table S1 in Supplementary material) to provide a sampling frame that represents the observed range of (1) number of established non-native fish species in the county (Jacobs, 2014), (2) surface water area (U.S. Geological Survey, 2013), and (3) median household income (U.S. Census, 2015). Four counties were chosen from each of the Northeast, Northwest, and Southern regions of the state. These regions represent three out of the five management regions defined by the IL-DNR. Additionally, we made the survey available to boaters online. Full details are described in Cole et al. (2016).

Respondents returned 515 surveys with the distribution roughly equal across counties and regions (see Table S1). Boaters who reported that they only launched their boat at a single waterbody during 2013 (n = 172; 33%) were excluded from further analysis because they pose no risk for spreading non-native species. Thirty-three respondents were removed as they did not provide their zip code and 18 were removed because waterbody locations could not be identified (e.g. illegible handwriting, incomplete information), leaving 292 surveys (57% of respondents).

The survey asked boaters to give their zip code of residence and the last five waterbodies in which they launched their boats during 2013. For the latter, respondents were asked to give the name of the waterbody, the nearest town, the state, and an estimate of the distance traveled from their home. These details allowed us to determine the waterbody visited even when its name was not unique (e.g., "Bass Lake"). We note that we asked boaters to list the last five independent waterbodies visited during 2013 and not the last five trips. If a boater's last three trips were all to the same waterbody, this waterbody should only have been listed once, and was coded as such in our dataset.

We asked boaters about the frequency with which they took actions to reduce the risk that non-native species were unintentionally transported along with their boat. To do this, we identified the three parts of a boat and its equipment – exterior (hull, engine and trailer), interior (including live wells and bilge), and fishing tackle – that have been the focus of outreach efforts. We asked boaters how often they take actions to ensure that each of these vectors are free of non-native species before they launch their boat in a different waterbody. Specifically, for the boat exterior we asked how often respondents visually inspected the outside of their boat and removed organisms, rinsed their boat with high-pressure and/or hot water, dried their boat with a towel, and how often they allowed their boat to dry for at least five days. For boat interior, we asked how often they drained water from live wells, bilge, and bait buckets. For fishing tackle, we asked how often boaters inspected all angling equipment and removed organisms between waterbodies. Boaters responded separately for each action on a five point Likert scale (0 = Never; 1 = Rarely; 2 = Sometimes; 3 = Often; 4 = Always, with an option of N/A for not applicable). Using the same scale we asked boaters how often they *intentionally* move and release organisms among waterbodies.

We considered that taking at least one of the recommended actions for each vector was sufficient to substantially reduce the risk of transport for that vector. Thus, for each vector (exterior, interior, tackle) we classified respondents according to whether they *Always* perform AIS prevention behaviors (i.e., they responded that they *Always* take at least one of the recommended actions) or perform AIS prevention *less than Always* (i.e., highest response for recommended actions is *Never*, *Rarely*, *Sometimes* or *Often*). For our network analyses (see below) we assumed a low risk for species spread associated with the given vector when a respondent reported that they *Always* take at least one of the recommended actions, while boaters that perform actions *less than Always* pose a greater risk. For intentional transport we considered that boaters posed low risk of transport only if they reported that they *Never* engage in such activities.

2.2. Distance between boaters' residences and waterbodies

We used the National Hydrology Dataset (U.S. Geological Survey, 2013) and ArcGIS 10.1 ESRI software (ESRI, 2014) to determine Euclidean distance between the centroid of boater residence zip codes (i.e., source) and the centroid of each waterbody that they visited (i.e., destination). For all rivers, and for lakes larger than 25 km^2 (see Table S2 for names and sizes of waterbodies), we calculated the distance from source to the town that the respondent reported was nearest to their destination. This was considered a good proxy for actual launch location because boat launches are often located in towns. Distances between source and destination were calculated in R (R Core Development Team, 2013) and the distances traveled for *Always* and *less than Always* boaters compared using Welch's *t*-test.

2.3. Networks of waterbodies and Boater movements

Network analysis was used to investigate movement of boaters among waterbodies. To ensure sufficient data, we restricted our analyses to waterbodies that were visited five or more times by the pool of survey respondents. First, we created a 'full' network of boater travel among these waterbodies using ORA software (Carley et al., 2013). This network includes all travel by all boaters. Next, we created networks to represent potential AIS transport via each of the four vectors. For the 'boat exterior' network, we removed all boaters from the 'full' network that reported that they *Always* take efforts to reduce their risk of spreading AIS on the exterior of their boats. The same pattern was followed to create 'boat interior', and 'fishing tackle' networks. For the 'intentional movement' network we included only boaters who reported that they *Rarely*, *Sometimes*, *Often,* or *Always* intentionally moved live organisms. Finally, we created a 'potential spread' network that includes all boaters who, for at least one vector, did not *Always* engage in behaviors to reduce spread.

Within each network the nodes are independent waterbodies and the edges are links between waterbodies that were realized during 2013 by actual boater movements. For each network we calculated density and average shortest path length (Wasserman and Faust, 1994; Carley et al., 2013). Density is the proportion of all possible links between nodes that are realized by edges, and ranges from 0 (no connections) to 1 (every possible connection). This metric indicates how tightly boater travel connects the network of waterbodies. Higher density values indicate greater potential for the spread of non-native species, assuming all other boat vector characteristics were equal. Average shortest path is the average number of steps required to travel from each node in the network to each other node, moving only along edges. It gives the average number of 'hops' a species needs to take to move among waterbodies, with lower values indicating that movement is more likely.

We determined from Jacobs (2014) and U.S. Geological Survey (2012) the number of non-native species that are reported to be established in each of the highly visited waterbodies, and we used Pearson's correlation coefficient to examine the relationship between number of non-native species and visits by boaters. This correlation was calculated for each network. Lake Michigan was excluded from this analysis because it is an outlier in terms of size, habitat, connections to other waterbodies, and the number of established species (see Table 1).

3. Results

3.1. Illinois Boater travel patterns

Boaters reported visiting an average of 2.8 ± 0.1 (mean ± se) waterbodies during 2013, yielding 823 unique visits across 264 waterbodies. These waterbodies are located in the U.S. states of Illinois (n = 111), Wisconsin (n = 84), Minnesota (n = 17), Michigan (n = 13), Florida (n = 6), Missouri (n = 4), Arkansas (n = 3), Tennessee (n = 3), Alabama (n = 2), Kentucky (n = 2), Mississippi (n = 2), Texas (n = 2), Maine (n = 1), North Dakota (n = 1), and Ohio (n = 1). Thirteen boaters visited a total of 12 waterbodies in Canada. Sixty-one percent of all reported visits were to waterbodies in Illinois.

Forty-seven percent of waterbodies visited were within 50 km, and 63% within 100 km, of boater residences (Fig. 1). The modal distance of waterbodies from residences was 13.7 km and the average was 175.9 km, giving a strongly skewed distribution. Twenty-eight waterbodies, all in Illinois, were visited five or more times during 2013 by survey respondents (Table 1). These are represented as nodes in the 'full' network diagram (Fig. 2) and are connected by 82 unique edges, each corresponding to one or more boaters traveling between given nodes. The network has density of 0.217 and average path length of 2.280. The number of non-native species recorded from each waterbody varied widely, with a maximum richness of 93 in Lake Michigan, though this was a substantial outlier (Table 1, Fig. 2). Most waterbodies (n = 21) in the network have eight or fewer reported established non-native species, and three have zero.

3.2. Boater efforts to reduce invasion risk

Of the 292 respondents, 72% percent reported *Always* performing a behavior to clean their boat's exterior, 78% reported *Always* cleaning their boat's interior, 55% reported *Always* cleaning their fishing tackle, and 96% reported that they *Never* intentionally transported or released organisms. Boaters who *Always* performed behaviors to clean the boat exterior, boat interior, fishing tackle, or reported that they *Always* did not intentionally transport organisms, traveled longer distances (183.6 ± 10.6 km, 184.7 ± 10.9 km, 195.8 ± 12.5 km, and 176.6 ± 9.8 km, respectively) than boaters who performed behaviors *less than Always* (153.5 ± 21.3 km, 141.2 ± 19.7 km, 148.9 ± 14.7 km and 160.9 ± 42.3 km, respectively), but the difference was only significant for the fishing tackle vector (*t*-test (821) = 2.42, p = 0.02).

The four networks created for specific vectors varied in the number of waterbodies included, network density, and average path length. The 'boat exterior' network contains 25 waterbodies with a density of 0.153 and average path length of 2.612 (see Online Material Fig. S1). The other networks created were for 'boat interior' (waterbodies = 21, density = 0.570, path length = 4.086; Online Fig. S2), 'fishing tackle' (waterbodies = 27, density = 0.185, path length = 2.293; Online Fig. S3), and 'intentional spread' (waterbodies = 14, density = 0.220, path length = 1.744; Online Fig. S4). Note that density and average path length are not directly comparable across networks with different numbers of waterbodies (nodes). Finally, the 'potential spread' network includes all 28 nodes included in Figs. 1 and 72 unique links among these waterbodies (density = 0.190; average path length = 2.327; Fig. 3).

There was not a significant correlation between the total number of visits to a waterbody and the number of AIS established there (Pearson's r = 0.375, p = 0.053). For the reduced networks, there were significant positive correlations between number of non-native species and number of visits for boaters who performed *less than Always* behaviors for the 'potential spread' network (r = 0.375, p = 0.009), and for boaters who *less than Always* cleaned their boat interior (r = 0.66, $p < 0.001$) and fishing tackle (r = 0.59, p = 0.001). Correlations were not significant for boat exterior (r = 0.257, p = 0.194) or intentional transport (r = 0.142, p = 0.481).

4. Discussion and conclusions

Although more than half of all respondents report that they always

Table 1
Waterbodies that received five or more visits from survey respondents during 2013. Subsequent columns are the number of visits by boaters that did not *Always* perform behaviors to reduce risk of AIS spread on the vector listed.

Waterbody	Number	Number of AIS recorded[a]	Total Visits	Visits by boaters with < *Always* behaviors [by vector]				
				Boat Exterior	Boat Interior	Fishing Tackle	Intentional Release	All vectors combined
Lake Michigan	1	93	30	9	0	16	0	17
Illinois River	2	27	42	12	11	29	2	31
Mississippi River	3	23	26	9	6	16	3	17
Fox River	4	19	7	2	6	4	0	7
Kankakee River	5	18	9	0	3	6	0	6
Mazonia Lakes	6	18	5	3	3	4	0	4
Rock River	7	13	40	7	8	21	2	26
Cedar Lake	8	8	9	6	3	6	1	7
Devils Kitchen Lake	9	8	13	7	3	6	1	10
Ohio River	10	8	6	1	0	3	1	4
Crab Orchard Lake	11	6	38	18	9	18	3	24
Heidecke Lake	12	6	13	4	3	7	0	7
Fox Lake	13	4	14	0	4	0	0	6
Lake of Egypt	14	4	27	9	4	10	3	16
Little Grassy Lake	15	4	12	7	4	7	0	8
Rend Lake	16	4	35	13	3	16	4	22
Clinton Lake	17	3	14	2	2	6	2	7
Lake Shelbyville	18	3	15	5	0	7	0	11
Pierce Lake	19	3	19	4	5	5	4	11
Evergreen Lake	20	2	5	3	0	3	0	3
Kinkaid Lake	21	2	10	5	2	4	1	8
Shabbona Lake	22	2	7	1	3	1	0	3
Lake Carroll	23	1	6	1	0	2	0	2
LaSalle Lake	24	1	5	2	2	3	0	3
Lake Victoria	25	1	5	1	0	1	0	1
Banner Marsh	26	0	12	5	2	4	1	6
Coal City Area Club	27	0	6	0	1	3	0	3
Sesser Lake	28	0	12	3	0	3	1	4
		Total	442	139	87	211	29	274

[a] Number of established AIS taken from Jacobs (2014) except for Lake Michigan, which is from USGS (2012).

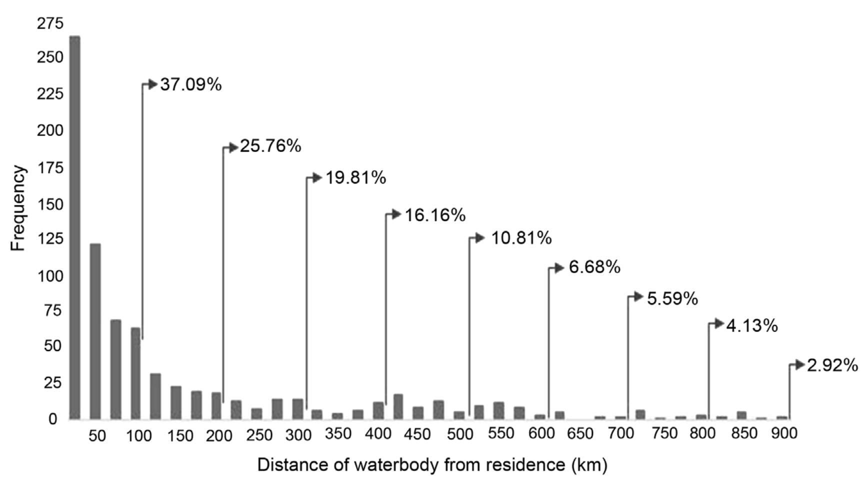

Fig. 1. Histogram showing frequency of trips to waterbodies that are different distances from boater residences (see *Methods* for details of how distances were calculated). Numbers to the right of arrowheads indicate the percentage of all trips that were longer than the specified 100 km interval.

take efforts to reduce risks of spreading AIS, there remains high risk of transport by recreational boaters across Illinois. This is demonstrated by the 'potential spread' network (Fig. 3) which contains all waterbodies and is only slightly less dense than the 'full' network (Fig. 2). While any reduction in network density is desirable because it is likely to reduce the rate at which species are moved, the fact that all lakes continue to be part of the network means that – even for the small subset of Illinois boaters that were used to create our networks – all of these lakes remain vulnerable to the introduction of new non-native species.

Cole et al. (2016) estimated that over $600,000 was spent on AIS outreach in Illinois during 2013, and this expenditure has likely been similar for several years. This is by far the largest investment made with the aim of preventing the spread of non-native species on recreational boats in the state. Outreach messages have been distributed across many platforms (Cole et al., 2016; Seekamp et al., 2016), and it is likely that the vast majority of Illinois boaters have been exposed to those messages. For example, signs at boat ramps are common, everyone purchasing an Illinois boating or fishing license receives a state handbook that includes information about preventing the spread of AIS (IL Department of Natural Resources, 2016), and bait and boating stores regularly display AIS outreach material. The results presented here accord with results from Seekamp et al. (2016) to indicate that outreach efforts have successfully altered the behaviors of many boaters (see Table 1), and all else being equal this will result in decreased AIS

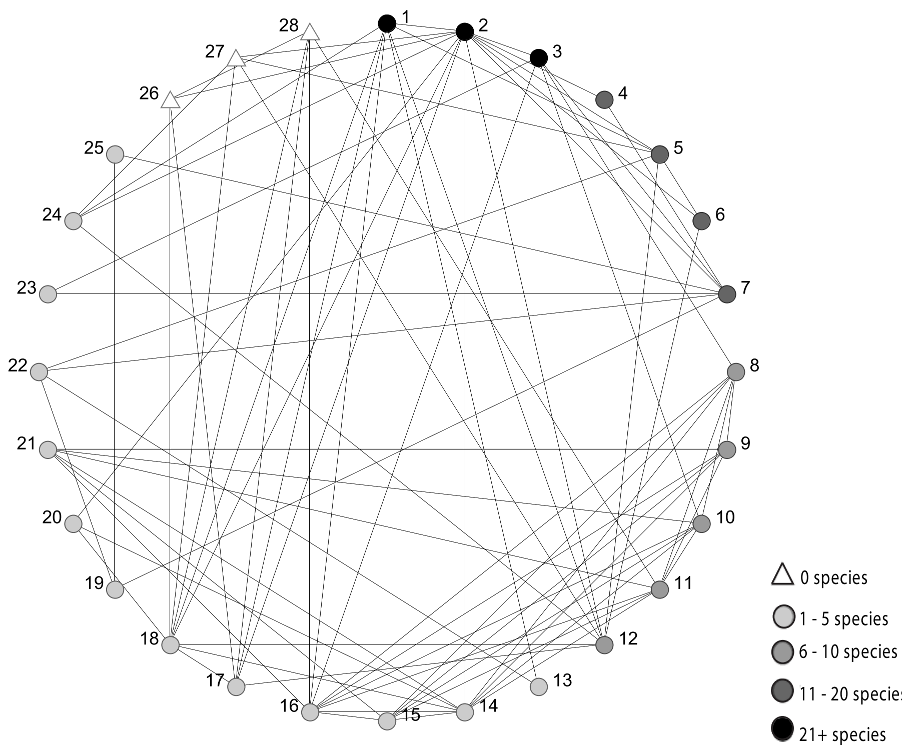

Fig. 2. 'Full' network of waterbodies (n = 28) visited by survey respondents five or more times during the summer of 2013. Shading of nodes indicates the number of established non-native species (from Jacobs, 2014; U.S. Geological Survey, 2012). Density = 0.217. Average path length = 2.280.

transport. Despite this, we show that benefits from the conservation behaviors of the majority of boaters are partly negated by the remaining boaters. For example, just four percent of boaters reported that they sometimes intentionally move organisms, but the network across which these boaters travel (Fig. S4) includes half of the waterbodies in the full network.

The boaters who responded to our survey reported traveling longer distances than boaters from nearby states. Buchan and Padilla (1999) surveyed boaters in Wisconsin and its neighboring counties (i.e., counties not in Wisconsin but that border Wisconsin) and estimated that 8.4% of the trips made by boaters were greater than 50 km, and 3.6% were greater than 100 km. The corresponding results from this study were 37% and 26%, respectively. In Wisconsin, the average distance traveled by boaters was estimated to be 34 km (Buchan and

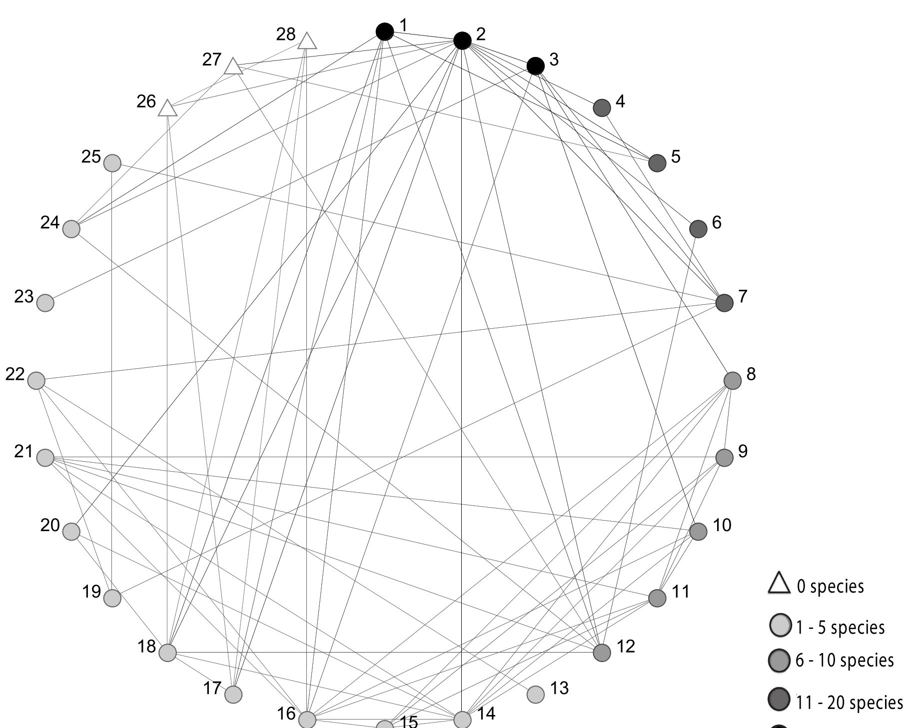

Fig. 3. 'Potential spread' network, showing waterbodies (n = 28) visited by boaters who posed risk of organism transport for at least one of the boat exterior, boat interior, fishing tackle, or transport and release vectors during the summer of 2013. Shading of nodes indicates the number of established non-native species (from Jacobs, 2014; U.S. Geological Survey, 2012). Density = 0.190. Average path length = 2.327.

Padilla, 1999), and Leung et al. (2006) estimated that trips made by Michigan boaters between their homes and destination waterbodies were an average of 74 km. The corresponding value from our survey of Illinois boaters was 175 km. Although each of these estimates was derived using slightly different methods (see original studies for full details), the magnitude of differences is large and likely relates to the density of waterbodies in each state. Illinois contains 1791 inland (i.e., excluding Lake Michigan) waterbodies of 4.45 ha (11 acres) or larger (IL Department of Natural Resources, 2000), Wisconsin contains 5605 waterbodies of 4.45 ha or larger (WI Department of Natural Resources, 2018a), and Michigan contains 6809 waterbodies of 4.05 ha (10 acres) or larger (MI Department of Natural Resources, 2018). Additionally, many waterbodies in Illinois are not publicly accessible, and waterbodies are densely clustered in the northeast region of the state and relatively sparse elsewhere (IL Department of Natural Resources, 2000). These reasons each indicate that Illinois boaters need to travel further to access waterbodies, and are reasonable explanations for the higher travel distances recorded.

Thirty-seven percent of the visits made by survey respondents were to waterbodies more than 100 km from their residences, and many were to other states, indicating that Illinois boaters may play a particularly important role in the regional spread of AIS. An important consequence of Illinois boaters' travel habits is that they have the potential to move non-native species over longer distances than their counterparts from other states. This means that AIS are more likely to both arrive in Illinois from other states as boaters return from longer trips, and that they are more likely to spread from Illinois to other regions. However, such risk of spread over very long distances may be reduced because longer travel times can increase desiccation (mass loss due to drying) and mortality of AIS, but many species have been shown capable of surviving on boats transported over long distances. For example, quagga mussels were introduced to and subsequently established in Lake Mead (Nevada and Arizona), surviving overland transport distance of roughly 3,000 km from the nearest other known invaded waterbody (Wong and Gerstenberger, 2011), and aquatic plants can experience desiccation of over 90% and remain viable (Barnes et al., 2013).

We did not find a statistically significant relationship between the number of times that a waterbody was visited by survey respondents ('full' network) and the number of established AIS in the waterbody. However, when we removed those boaters who *Always* take recommended actions to reduce AIS risk across all vectors ('potential spread' network) there was a significant positive correlation between number of visits to a lake and the number of established AIS. This was true for the 'boat interior' and 'fishing tackle' networks, but not for 'intentional release' and 'boat exterior' networks. We speculate that this may indicate that boats used for fishing are important vectors of non-native species. Such boats are much more likely to have fishing tackle, and to have live wells, the latter of which can transport organisms without any risk of desiccation. At a higher level these results broadly support the hypothesis that boaters who do not take recommended actions are more likely to move AIS, and thus that the lakes visited most often by these boaters will have the greatest numbers of AIS.

Given that outreach efforts in Illinois are well-developed and widespread, it is likely that achieving further reductions in AIS transport by boaters will require new approaches. One option adopted elsewhere is direct inspection of boats and equipment for AIS. In Idaho and other U.S. states there are inspection stations on highways that require boaters to pull over and have their boats checked for AIS, and volunteers in Wisconsin inspect > 100,000 boats annually as they are launched at, or removed from, popular waterbodies (Wisconsin Department of Natural Resources, 2018b). While direct inspection is labor intensive it may be particularly effective because experts are taking time to inspect and clean boats, and because it offers the opportunity for face-to-face interactions and discussions of AIS issues. Importantly, it should access all boaters so that even those who have not modified their behaviors are reached. Although some states allow fines for transporting a boat that has non-native species attached, these fines have been applied in only a small handful of instances, with management agencies generally preferring to develop trust with boaters through education and outreach. This is similar to approaches elsewhere (e.g., Wald et al., 2018) where more trusted sources have been shown to have greater influence over individual behavior.

In Illinois, a relatively small number of waterbodies appear to be important for connecting the networks of boater movements. Rivers may be difficult to manage because they can have many access points, but lakes and reservoirs offer better opportunities for intercepting boaters. In particular, boating in the south of the state is dominated by a small number of large reservoirs (waterbodies 8, 9, 11, 14–16, 18, 21 & 28 in Table 1 and Figs. 2 and 3), and the north of the state is dominated by Lake Michigan. Targeting these waterbodies for boat-ramp inspection and cleaning stations could substantially interrupt the flow of AIS, and would offer the opportunity for face-to-face interaction and outreach.

At a higher level, we suggest that the current approach to outreach, in which campaigns are evaluated based on the number of contacts made with boaters may need to change. Cole et al. (2016) showed that conservation behaviors were practiced at similar rates across Illinois even though some regions had much greater investment in outreach. This suggests that simply applying more of the same type of outreach may not increase adoption of conservation behaviors. Instead, outreach messages should be targeted at those boaters who have not yet adopted the recommended behaviors, and research should be conducted to determine what type of outreach approaches are most effective. Kemp et al. (2017) conducted focus groups to investigate responses of Illinois recreational water users to different AIS outreach messages. While the focus groups were too small to make general conclusions, this researched clearly showed that not all recreational water users respond in the same way to different outreach messaging, and thus that multiple approaches tailored to different audiences are needed. A recent review (Byerly et al., 2018) of the effectiveness of different strategies for changing environmental behaviors found that a range of approaches can be effective, but that they are not equally effective across environmental issues. For example, Byerly et al. (2018) found that communicating that water conservation is a 'norm' (i.e., that most people do it) caused people to reduce water use, but that the same approach was less effective for motivating other environmental behaviors, such as reducing waste or selecting environmentally friendly transportation modes. Likewise, asking people to make commitments to engage in environmental behaviors was effective for modifying some behaviors but not others.

There is little available research dealing with the effectiveness of outreach campaigns for motivating behaviors that reduce spread of AIS on recreational boats. Seekamp et al. (2016) investigated boater knowledge and behaviors related to a specific outreach campaign, and Cole et al. (2016) looked at the links from outreach agencies, via outreach materials, to boater knowledge and boater behaviors. Both projects showed that boaters with more knowledge of AIS are more likely to engage in behaviors to prevent their spread, although the effect size was not large in either study. Importantly, neither study, nor any others of which we are aware, used before and after methods to determine how specific outreach approaches affect behaviors. Thus, while it is reasonable to expect that some outreach strategies will be more effective than others, the lack of research makes it impossible to determine what these strategies are. Such research could improve and justify the investments made in outreach.

There are three important caveats to keep in mind for the interpretation of our work. First, our survey results likely overestimate the rate at which boaters are performing recommended behaviors to limit the spread of AIS. Our survey was sent to a random group of all boaters in Illinois counties and respondents are likely biased towards those aware of and concerned about invasive species. Further, people tend to self-report higher rates of positive behaviors than they actually perform

(Dillman et al., 2014). This leads to the conclusion that the true connections among waterbodies are likely stronger than those suggested by our networks. Determining the extent to which our results are different to reality would require random selection of Illinois boaters for direct observation coupled with surveys of those same boaters.

The second caveat is that the results of the network analysis were based on the twenty-eight waterbodies that were visited by boaters five or more times during the summer of 2013. We did not include any links to or from other waterbodies, and our networks are thus visualized as being isolated from all other waterbodies. In reality, the 28 waterbodies are likely connected to all others in Illinois, and we know that they are connected to waterbodies in other states and Canada. The U.S. Coast Guard (2016) reported that there were 242,275 registered boats in Illinois in 2016, illustrating our small sample size and making it clear that a larger survey would identify many more waterbodies and connections.

Third, the distances calculated between waterbodies and residences may not represent the actual length of transit. For example, in the same trip a boater may visit two lakes that are close to each other but far from their residence. In this case, the distance to the first lake would be as shown in Fig. 1, but the distance traveled from the first to the second would be substantially shorter. This could increase risk of organism transport because desiccation would be less than suggested by the distance shown in Fig. 1. Related to this, our results do not account for time of transit between waterbodies. If a boater visited a waterbody some weeks after visiting the prior waterbody this may lead to a much lower risk of transporting live organisms than if they traveled there directly.

Public education and outreach efforts are the main method used in Illinois to prevent non-native species introduction and spread. The belief is that if individuals are made knowledgeable of this conservation problem they are more likely to adopt and perform behaviors that will solve the problem (Hungerford and Volk, 1990). Our results show that efforts in Illinois have achieved high adoption of behaviors designed to reduce non-native species introduction and spread. Despite this, the networks over which non-native species spread remain intact and the travel patterns of Illinois boaters make it likely that new species will be introduced to the state, and that species already established will continue to spread, possibly over long distances. Further efforts will be necessary to prevent the spread of AIS throughout and beyond Illinois.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2018.06.078.

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